C. Hydrologic Change

Hydrologic Change

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Introduction

The hydrologic performance of forested watersheds is affected by three broad classes of processes:

1. Delivery of water to the forest is determined by rates of condensation and precipitation (rain and snow), largely controlled by climate;

2. Delivery of water to the forest floor is determined by interception and snowmelt, which in turn are largely controlled by vegetation;

3. Delivery of water to streams is determined by the balance between precipitation, evapotranspiration, and runoff-generating processes, the latter involving several surface and subsurface pathways.

Forest practices can alter each of these processes in several ways. Opening of the canopy by timber harvest can cause greater snow accumulation in winter (because snow on the ground is less affected by interstorm melt than is snow in the canopy) or increased snowmelt in spring (by removal of overstory shade); openings also allow accelerated melt rates, due to increased radiation and wind-assisted flux of sensible and latent heat to the snowpack. Maximum accumulations are found in openings on the order of three to four tree heights in width; at widths greater than 10-20 tree heights, snow accumulation may be less than that under a canopy, owing to wind redistribution of snow (Troendle 1983). The loss of vegetative cover may reduce rates of interception and evapotranspiration, leaving more water to enter the ground. In some cases, loss of forest canopy may actually decrease soil-water input, through reduction in the amount of fog drip. Compaction of the soil on roads and skid trails reduces local infiltration, increasing the likelihood of overland flow at the expense of slower subsurface pathways. The magnitude or timing of streamflows may be altered because of the augmentation of storm-runoff volume due to enhanced soil moisture or snowmelt, because of reduced detention storage on the hillslope, or because road construction or other surface disruption makes the drainage network more efficient in conveying runoff.

Thus, forest practices can change the magnitude and timing of streamflows. Whether or not any of these changes combine into cumulative effects depends on the precise character of the hydrologic changes in a specific basin. The methods described herein assume that the greatest likelihood for causing significant, long-term cumulative effects on public resources via alteration of forest hydrologic processes is through the influence of timber harvest on snow accumulation and melt during rain-on-snow (ROS) storm events (Harr 1981, 1986; Coffin and Harr 1992). Cumulative effects caused by forestry-induced changes in seasonal snowmelt, low flows, water yield, and flow routing are generally less likely, but may be important in certain watersheds.

These are briefly discussed at the end of the analysis procedure section, but no formal procedures for addressing them are included at this time.

Critical Questions

The purpose of the hydrologic change module is to address the following key questions:

What are the current watershed conditions influencing hydrologic response?

What is the history of floods and disturbances of hydrologic significance in the watershed?

What is the influence of land use on runoff during storm events which generate peak flows?

What are the effects of changes in runoff on flood peaks?

What are the effects of changes in peak flows on public resources?

The procedures for answering these key questions rely on a variety of tools, including maps, remote sensing (Landsat) imagery, climate and streamflow information, and hydrologic models. These tools are used to calculate the effects of changes in forest cover on snow accumulation, snowmelt, and runoff during a simulated storm event.

Assumptions

A number of assumptions underlie the approach developed here. The most fundamental assumption is:

- *The greatest likelihood for causing significant, long-term cumulative effects on public resources via alteration of forest hydrologic processes is through increases in peak flows attributable to the influence of timber harvest on winter snow accumulation and melt rates during rain-on-snow events.*

Other assumptions include:

- Regional flood-frequency regression equations, including their explicit estimates of confidence, provide a reasonable framework for evaluating the effects of forest harvest on peak flows over basin-scale areas.

- The effects of historically changing forest characteristics on the regional regression equations cannot be evaluated. The equations were based on data collected under a variety of land uses and forest patterns, including undisturbed, disturbed, and mixed conditions. However, for the purposes of this analysis, it is assumed that the regression equations predict flows under hydrologically mature (pre-disturbance) conditions.

- Although they do not necessarily occur together, it is appropriate to relate storms and flows having the same recurrence intervals (e.g. the 2-year storm and the 2-year flow, each having a 50% probability of exceedance).

- Snow measurements (recorded by the Cooperative Snow Survey and the National Weather Service) are made under a variety of forest stands; we do not know the conditions at most stations. In addition, snow accumulation is not a function of elevation alone, and the relationship is quite variable. We assume here that the snow regression equations derived from the measurements represent hydrologically mature conditions.

- The U.S. Army Corps of Engineers' snowmelt equation is appropriate for estimation of melt under ROS conditions.

Overview of Assessment and Products

The objective of the hydrologic assessment is to evaluate how forest practices may critically alter the hydrology of the WAU. This is accomplished by addressing the critical questions presented above. During the course of the assessment, the analyst will attempt to establish:

- The *hydrologic conditions and characteristics of the watershed* influencing peak flow response to land use;

- The *historic patterns of peak flows and other disturbances of hydrologic significance* in the watershed;

- The *change in water available for runoff* with changes in forest vegetative cover;

- The *change in flood peaks* associated with changes in runoff;

- The *potential effects on public resources* of changes in flood peaks.

Each of these objectives is an integral component of the hydrologic assessment. Together, this information provides a means for evaluating potential peak flow response to changes in vegetative cover conditions in the watershed.

The analyst evaluates the hydrologic condition of the watershed by identifying the general watershed characteristics that are likely to significantly affect storm runoff, including climate, physiography, and land use. For purposes of the assessment described in this manual, land uses other than managed forest are considered to have potentially important effects on peak flows, but these effects are assumed not to change over time. Operations occurring in managed forests may also affect storm peaks, but these effects are likely to change in response to harvest and regrowth of forest stands.

The analyst utilizes precipitation zones which spatially define the likelihood and magnitude of hydrologic response to forest practices at any point in the watershed. Considering both land use and climatic factors, the analyst stratifies the hydrologic analysis units within the watershed representing sub-basins similar in responsiveness to forest management effects. These are mapped as the hydrologic analysis units, and the areal distribution of land-use/cover types and precipitation zones is summarized on Form C-1: Basin Acreage by Precipitation Zone and Land-use/Cover Type. These hydrologic analysis units are subsequently evaluated for sensitivity to forest practice effects using the ROS analysis. The analyst also identifies the public works which may affect or be affected by changes in flood peaks in the watershed and places them on the map.

The analyst attempts to establish the historic patterns of peak flows and upslope disturbances which may affect hydrologic response, including changes in land use. From this information, the analyst may be able to identify changes in hydrologic response attributable to individual or cumulative disturbances.

The next steps involve using a series of calculations to estimate the potential for changes in peak flows during ROS events due to harvest-related enhancement of snowmelt runoff. These calculations are performed for the outlets of sub-basins identified as hydrologic analysis units.

The standard hydrologic assessment described in this manual uses local climatic and hydrologic data and/or regional empirical relationships to estimate values for the processes which generate the water available for runoff

(WAR), including: (1) storm rainfall, (2) snow accumulation, (3) snowmelt. WAR estimates are then used to estimate peak flows.

Assessment of water available for runoff begins with establishing the baseline precipitation amounts associated with storm events having recurrence intervals of two to 100 years. The analyst determines the current vegetative condition of the watershed using data available from landowners, aerial photographs, or Landsat imagery. Using vegetative cover scenarios of "maximum hydrologic maturity" (hydrologically mature), "current condition", and "minimum hydrologic maturity" (hydrologically immature), the analyst determines the snow accumulation as a function of elevation and forest cover, and snowmelt as a function of wind speed, temperature, and precipitation. These meteorological variables are estimated for assumed "average" rain-on-snow conditions, as well as for "unusual" (deeper snowpack, warmer and windier weather) conditions. The snowmelt water equivalent (a function of forest cover) is added to the baseline estimates of precipitation to determine the WAR in each hydrologic analysis unit for each combination of storm intensity, vegetative cover condition, and recurrence interval. Results of this portion of the assessment are summarized on Form C-2: Summary of Water Available for Runoff.

Storm peak flows are determined using a regression equation correlating 24-hour precipitation with estimated or measured values of peak discharge. Applying WAR estimates to this equation will produce an estimate of peak flow for each scenario under consideration. Results of this assessment are summarized on Form C-3: Summary of Peak Discharge Estimates.

Once the increases in peak flows are estimated, the analyst must weigh the probability of significant hydrologic change under different land-use scenarios. This is done by evaluating potential effects on public resources attributable to flood peaks. Response ratings may be based solely on predicted increases, or may be augmented by further analysis of the direct impacts to specific resources (such as water depth for large floods relative to public works, or implications for bed scour frequency for fish habitat). These assessments will better address uncertainties, since little is known regarding the effects of changes in peak flows on fish habitat, and are recommended for a level 2 analysis. A narrative describing the implications of peak flow changes from managed forest zones (and recognizing the effects from other land use in the watershed) is the product of this portion of the assessment.

Qualifications

Expertise in applying hydrologic and hydraulic principles is required to effectively complete this assessment. In addition to completing the watershed analysis training provided by DNR, those conducting the hydrologic assessment must possess, at a minimum, the following skills, education, and experience.

Skills

- Understand the components (relevant processes and magnitudes) of the hydrologic cycle, as they pertain to forested areas;
- Understand principles of probability and statistics, as they apply to the frequency analysis of hydrologic processes.
- Be familiar with computer-based methods (spreadsheets, GIS, and computer models) for estimation of runoff;
- Be familiar with basic channel surveying techniques including determination of channel cross-sections, slope gradient, bankfull flow levels, flow resistance, and streambed particle size distribution;
- Understand basic principles of sediment transport.

Education and Training

Level 1:

Bachelor's degree in hydrology (or a related field such as civil engineering, geology, forestry, forest engineering, soils, etc.), with a significant amount of course work or other training (academic or commercial short courses, etc.) in hydrology (particularly hillslope hydrology in forested basins).

Level 2:

Level 1 qualifications, plus:

Graduate level course work in hydrology, fluvial geomorphology, river mechanics, or some closely aligned field that includes hydraulics of open channel flow, channel form and process, and sediment transport.

Experience

Level 1:

Two years of field experience in assessment or research regarding hillslope hydrology of forested and/or mountainous areas.

Level 2:

At least two years of field experience in assessment, scientific management, or research regarding hillslope hydrology, particularly the estimation of runoff from forested and/or mountainous areas and sediment transport in natural channels.

Background Information

The following materials are necessary to start the hydrologic change module.

Maps

- Official WAU base map;
- Topographic maps of the area *(U.S. Geological Survey 7.5-minute series,* 1:24,000 scale; available from commercial dealers, *DNR Photo & Map Sales (Olympia, (360) 902-1234),* and *USGS Western Mapping Center (Denver);*
- Maps of DNR precipitation zones (hard copy or GIS coverage at 1:100,000 scale) are available from *DNR Information Technology Division (360) 902-1544.*
- Annual and storm precipitation isohyetal maps can be found in the *NOAA Atlas* (Miller and others 1973); GIS coverage is available from *DNR Information Technology Division (360) 902-1544.*
- Maps of vegetation size and density for use in delineating land-use/cover types (hard copy or GIS coverage) are available *from DNR Information Technology Division (360) 902-1544.*

  or

Maps of vegetation age and type might be available from *land owners;* the *USGS* publishes some digital maps of land use and land cover.

Aerial photography

Recent air-photos may be useful in detecting changes in vegetation patterns since the Landsat imagery (upon which GIS interpretations are based) was acquired (mostly in 1988). These can be used directly to map the vegetative cover for the watershed.

Climate and streamflow data

Summaries of climatic data, including maps of mean annual precipitation, can be found in reports on the climate of Washington counties (see references for listing). Compilations of climatic data from stations reporting to the National Weather Service are available in paper format (monthly *"Climatological Data for Washington"* for all stations, and *"Local Climatological Data"* for first-order stations), and on CD-ROM (from private vendors). Data from snow courses and snow pillows, compiled by the Natural Resources Conservation Service (NRCS) are available in annual data summaries or on-line from the NRCS/WNTC computer (contact *NRCS at (509) 353-2341* for more information).

Flow data are available in USGS water-supply papers and open-file reports (summarized in Williams and Pearson 1985a,b; Williams and others 1985a,b), and on CD-ROM (from private vendors).

Analysis Procedure - Level 1

The standard hydrology assessment is described below. Information and products consistent with the standard assessment must be completed for each watershed analysis performed (including Level 2 assessments).

A Level 1 assessment will produce the standard products, and may result in indeterminate hazard calls. A Level 2 assessment is expected to address uncertainties identified in the Level 1 assessment; indeterminate hazard calls must be resolved at this level. It is important that both the nature and magnitude of uncertainties be identified so that subsequent decisions in the synthesis and prescription phases may account for them.

A Level 2 analysis should be invoked when analysts are not satisfied with their ability to answer one or more critical questions based on the standard methods. This may include more refined analyses of particular processes or sub-areas within the watershed. Level 2 assessment requirements are flexible, allowing the analyst to tailor the approach to best address unresolved issues. A Level 2 assessment is expected to produce the standard products augmented by additional information as required.

Products from the analysis consist of maps, forms, and narrative as identified in the "Hydrologic Assessment Report" section of this module. The maps provide a graphical depiction of the factors influencing the hydrologic condition of the WAU, while the forms provide an accounting trail of the information and observations used by the analyst in developing interpretations. These products facilitate the review process, and provide the necessary means to reevaluate hypotheses over time. It is important that narrative sections be concise; the focus should be upon summarizing results and explaining deviations from or additions to the standard methods.

Hydrologic Condition and Characterization of the Watershed

It is important to establish the hydrologic condition of the watershed to provide a context for potential changes in hydrology due to forest practices. The hydrologic condition is the integration of those general watershed characteristics that are likely to significantly affect storm runoff, including land use patterns, structural features disturbance history, and climate. Forest land use is considered explicitly in the module, while other land uses are noted but not specifically addressed.

Within the forest zone, the hydrologic response is likely to vary with precipitation/elevation (climate) zone and vegetative cover. Rain-on-snow conditions can occur at almost any elevation, depending upon the right combination of climatic variables. The highest probability of rain-on-snow conditions occurs in the mid-elevation rain-on-snow zone; the next highest probabilities occur within the adjacent rain-dominated and snow-dominated zones. The lowest probabilities occur within the lowland and highland zones. Based on these probabilities, the analyst can screen out portions of the WAU with a low potential for rain-on-snow enhancement of peak flows, and focus the analysis on the remaining portions.

Hydrologic Characterization

An initial characterization of the hydrologic regime is an important first step. A brief summary of amounts and seasonal distribution of precipitation, average daily flows, and peak flows can assist the analyst in determining which processes (rain, snowmelt, rain-on-snow) are most important in generating peak flows. A hydrologic summary will help the analysis team identify the land use effects potentially influencing hydrologic response, and determine whether the standard rain-on-snow peak flow methodology is appropriate. For instance, the standard model may be of little use in a basin where major peak flows are generated by spring snowmelt processes. Another example is where extensive impermeable surfaces produced by residential development are the major land-use influence to peak flows (Booth 1989). In these cases, the use of an alternative method of analysis (if available) would be justified.

The hydrologic characterization should contain the following basic information:

Precipitation

1. Annual total, forms (i.e., rain, snow, fog drip) and seasonal distribution.

   Sources: Isohyetal maps (NOAA), climate data.

Streamflow Regime

2. Seasonal distribution of daily and peak flows.

3. Peak flow-generating processes. This refers to annual and larger peakflows. Three categories — rain only, rain-on-snow or spring snowmelt —apply to most forested area. In many basins, the dominant process generating annual peaks varies between years. In some cases it is hard to distinguish between ROS and primarily rain peaks; in such cases you may need to investigate weather records immediately prior to known peak flow events.

4. Peak flow history. Collect all streamflow data for the WAU, or nearby watersheds if the WAU has no gages or a limited period of record. If a sufficient period of record exists for a gage within the WAU, generate an annual series to identify when major flooding events occurred. Regression analysis utilizing a nearby gage may be used to extend an incomplete record; if the WAU is ungaged, the annual series of a nearby gage may be used to estimate the temporal distribution and relative magnitude of historic floods.

Determine the baseline flood-frequency curves for the hydrologic analysis unit of interest, using the USGS regional regression equations (Cummans and others 1975) to calculate flows:

$$Q_R = a \times A^{b1} \times P_a^{b2} \times F^{b3}$$

where Q_R is the peak flow for recurrence interval R (R = 2, 5, 10, 25, 50 and 100 years), A is area of the hydrologic analysis unit (mi^2), P_a is the average annual precipitation (in.) for the basin, and F is the percentage of the unit normally covered by forest vegetation (50% = 50). The values of a, b_1, b_2, and b_3 are reproduced in Table C-2; they are arranged by the 12 regions shown in Figure C-4. (Note that for all of the regions in western Washington, F is insignificant in the regression, so b_3 is not given.)

If sufficient data are available, perform a log-Pearson type III frequency analysis on the annual series to estimate the 2, 5, 10, 25, 50, and 100 year floods. Flood frequency analysis results are recorded on *Form C-3 - Summary of Peak Discharge Estimates.*

Flood frequency and history information should be conveyed to the channel condition analyst, and retained for use later in this assessment.

Sources (#2-4): USGS (major source) or other flow data (Bureau of Reclamation, municipal data at water supplies, small hydro data).

Land Use Patterns

Divide the WAU into land use/cover types as defined in Table C-1. Use the DNR GIS coverage of vegetation size and density, local stand information, and aerial photographs. Use recent photos (if available) to identify changes made since the maps or coverage were created. Delineate the types on a map of the WAU to create *Map C-1 - Current Land Use and Vegetative Cover* (see example, Figure C-1). If less than 5% of the total area is in non-forest types, it may be delineated collectively as "non-forest".

Structural Features

Identify any dams, levees, irrigation diversions, or other public works that may affect or be affected by flow in the stream channel (you may wish to confer with the public works analyst). Show these features on a base map of the WAU. Consider how these structures may exacerbate or mitigate problems associated with peak flows, and briefly discuss those effects in the narrative.

Table C-1. Land Use/Cover Types and Description.

Land Use/Cover Type	Description
Forested (1):	
Hydrologically Mature	Maximum Hydrological Maturity >70% total crown closure AND <75% of the crown in hardwoods or shrubs
Intermediate Hydrologic Maturity	Intermediate Hydrologic Maturity 10%-70% total crown closure AND <75% of the crown in hardwoods or shrubs
Hydrologically Immature	Minimum Hydrologic Maturity <10% total crown closure AND/OR >75% of the crown in hardwoods or shrubs
Non-Forested (2):	
Urban	Residential/Commercial/Industrial
Agricultural	Cultivated and Grazing Lands
Open Water	Lakes, Ponds, Reservoirs Inundated Wetlands
Other	Naturally occurring open areas (e.g. talus slopes, meadows, barrens)

(1) Unmanaged or managed lands currently occupied by, or capable of growing, stands of trees of commercial size.

(2) Lands permanently converted from forest, or incapable of growing stands of trees of commercial size.

Hydrologic Analysis Units

Delineate precipitation zones (as defined by the DNR Forest Practices Division) on the base map of the WAU. Using a topographic map at the same scale as the base map, delineate the sub-basin draining to the outlet of each DNR Type 3 stream. Overlay these two maps and determine the proportion of each sub-basin in each precipitation zone. Sub-basins with greater than 75% of their area in either the lowland or highland zones are initially assigned a low hazard rating for rain-on-snow and may be excluded from the remaining portion of this assessment (Note: This rating may be modified if physical or anecdotal evidence suggests that rain-on-snow enhancement of peak flows is a significant factor in a particular sub-basin). The remaining Type 3 sub-basins are identified as *hydrologic analysis units.*

Additional hydrologic analysis units include:

1. the entire WAU;

2. at the location of any stream gage with a useful period of record (generally 10+ years);

3. at the location of any structural features identified by the public works analyst as having moderate or high vulnerability to peak flow changes;

4. at additional locations of interest, in consultation with channel and fish habitat analysts. To properly consider scale, there should be one hydrologic analysis unit defined for each increase in stream order above that represented by the Type 3 streams.

Note that it is possible for hydrologic analysis units to overlap; analyses and interpretations for overlapping units should be conducted independently of each other.

Hydrologic analysis units, stream gages, vulnerable structural features, and identified locations of interest should be identified on *Map C-2 - Hydrology Base Map* (see example, Figure C-2). Multiple base maps may be required to properly depict all the items properly. Within each hydrologic analysis unit, calculate the percent area for each combination of land use/cover type and precipitation zone. Summarize the information on *Form C-1 - Basin Acreage by Precipitation Zone and Cover Type* (see example, Figure C-3).

In the narrative section, discuss which areas of the watershed have a large percentage of forested land, especially in rain-dominated, rain-on-snow, and snow-dominated areas. Also, discuss how other land uses such as urban and agricultural land may affect the hydrologic behavior of the watershed.

Disturbance History

From aerial photographs or anecdotal information, identify the time and location of major upslope disturbances in the WAU, including extensive fire, insect and disease outbreaks (where they may affect hydrologic maturity through defoliation), and mass wasting events which contributed substantial amounts of sediment (confer with the mass wasting analyst). Look for obvious correlations between these disturbances and changes in temporal flooding patterns (note: it may be necessary to obtain a partial duration series to conduct this portion of the analysis). Disturbance information is summarized in narrative form and conveyed to other module analysts (mass wasting, channel, surface erosion).

Water Available for Runoff

The primary mechanism by which forest practices can affect peak flows is assumed to be alteration of snow accumulation and melt rate in response to changes in forest canopy density (Harr 1981, 1986; Coffin and Harr 1992). This phenomenon may occur at any elevation from sea level to mountain peaks, but it most commonly occurs between approximately 1200 and 4000 feet elevation (the "rain-on-snow" zone). At these elevations, and especially on the west side of the Cascade Mountains, shallow snowpacks that accumulate during the winter may entirely melt under the relatively warm and windy conditions associated with large frontal storms.

This portion of the analysis uses an empirical approach to estimate rain-plus-snowmelt inputs to the soil surface of each hydrologic analysis unit. The process described below must be repeated for every analysis unit defined. Estimation of the WAR requires determination of a baseline 24-hour precipitation amount for a given return interval. To this is added an estimated snowmelt, which is obtained by subjecting a model snow accumulation to a simulated 24-hour storm. The model snow accumulation and simulated storm parameters (air temperature, wind speed, and precipitation amount) are obtained from regional equations and graphs provided in the module, or are derived by the analyst from local data. Values for these parameters are modified across the landscape with respect to elevation and vegetative cover.

The credibility of the WAR calculations are based largely on the validity of the weather conditions used in their calculation. Among completed applications of this peakflow method to date, local data have been used to develop input data for each of the follow inputs: temperature, windspeed, snowpack and baseline streamflows. Although substantial weather data were used to derive the regional relationships for temperature, wind and snowpack provided in the module, these values do not account for the substantial variability within regions. For this reason, it is important to use local data, either to verify the reasonableness of values obtained from the regional relationships, or to replace them, if data is sufficient. Weather data need not have been collected within the WAU to be valid, as long as conditions at the collection station (elevation, topography, etc.) were similar, and the rationale for their use is clearly documented in the report. Sources of data include U.S. Weather Service publications, NRCS snow survey publications and research plot data (e.g., Coffin and Harr 1992).

To properly evaluate the range of conditions under which rain-on-snow generated WAR may occur, a number of scenarios are considered. Each scenario represents a particular combination of three factors: precipitation amount, storm type, and hydrologic maturity of the WAU.

Precipitation amounts used in this assessment are 24-hour totals for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals.

Two storm intensities are considered:

- an "average" storm, representing a typical rain-on-snow event, and using mean values of storm temperature, wind speed, and snow accumulation;
- an "unusual" storm, representing a less frequent, more intense event, and using the mean value plus one standard deviation for storm temperature, wind speed, and snow accumulation;

Three vegetative cover conditions are considered:

- "maximum hydrologic maturity" classifies all forested lands (i.e. lands not classified as urban, agricultural, or open) as hydrologically mature (as defined in Table C-1);
- "current condition" represents the current distribution of land-use/ cover types;
- "minimum hydrologic maturity" classifies all "forested" lands as hydrologically immature (as defined in Table C-1).

An estimate for WAR is generated for each of the 36 scenarios (6 precipitation events x 2 storm intensities x 3 vegetative cover conditions). It is recommended that the analysis procedure be performed on a spreadsheet or within a GIS, especially if there are many hydrologic analysis units.

Note: If two or more hydrologic analysis units are expected to have similar peak flow responses, (by virtue of having similar proportions of area in each land use/cover type and precipitation zone), then one unit may be selected as an “indicator”; analysis results for this unit will apply to the remaining units.

Baseline Precipitation

For each of the designated recurrence intervals, determine the average values of the 24-hour precipitation ($P_{24/R}$, where R is the recurrence interval) using the NOAA Atlas (Miller and others 1973) or DNR GIS coverage. If estimating visually from the atlas, use precipitation amounts at the high end of apparent averages for the hydrologic analysis units; if using GIS, more exact area-weighted averages can be calculated. Convert the values for $P_{24/R}$ to centimeters.

Snow Accumulation

Snow accumulation and melt are determined by considering the effects of forest cover on wind speed, storm temperature and snow accumulation (Coffin and Harr 1992).

Estimate an average snow accumulation for each precipitation zone in the basin, using the relationship between average January 1 (nominal) snow-water equivalent and elevation (Brunengo unpublished):

$$SWE_{z1} = d_1 + (d_2 \times E_z) + (d_3 \times E_z^2)$$

where SWE_{z1} is the snow-water equivalent (cm), E_z is the mean elevation of the precipitation zone (m), and d_1 and d_2 are regional coefficients given in Table C-3; regional boundaries are shown in Figure C-5. If local data are available (SNOTEL data from NRCS, Summary-of-the-Day data from NWS), a more basin-specific relationship can be developed, especially if the equation results seem unreasonable. The result is the basis for an “average” snow accumulation, to be modified for vegetative cover conditions in a later step.

Using the appropriate standard error of the estimate (SEE) from Table C-3, estimate the basis for an “unusual” snow accumulation:

$$SWE_{z2} = SWE_{z1} + SEE$$

Figure C-1. Example: Map C1-Current Land Use and Vegetative Cover.

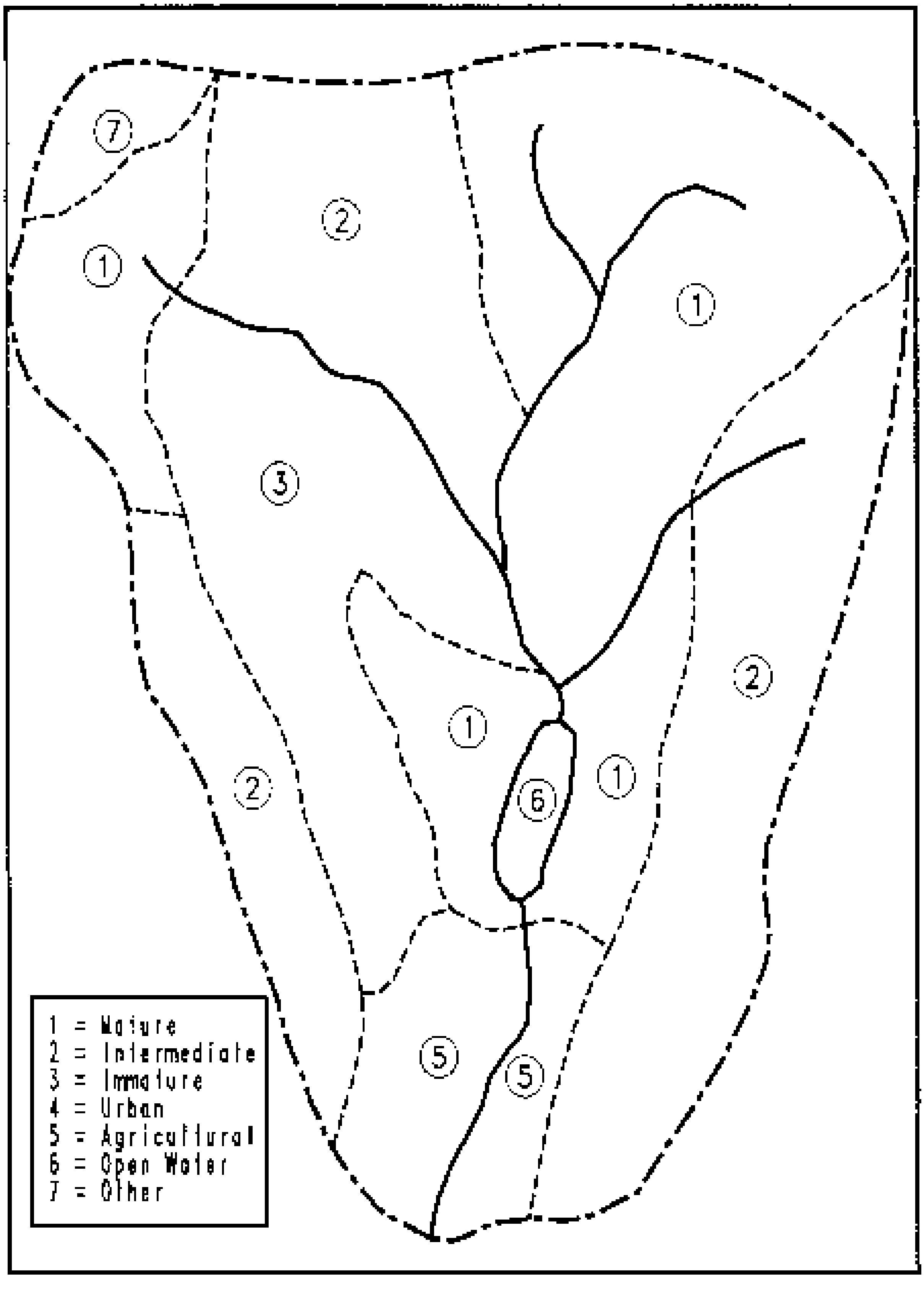


Figure C-2. Example: Map C2-Hydrology Base Map Showing Hydrology Analysis Unit 2.

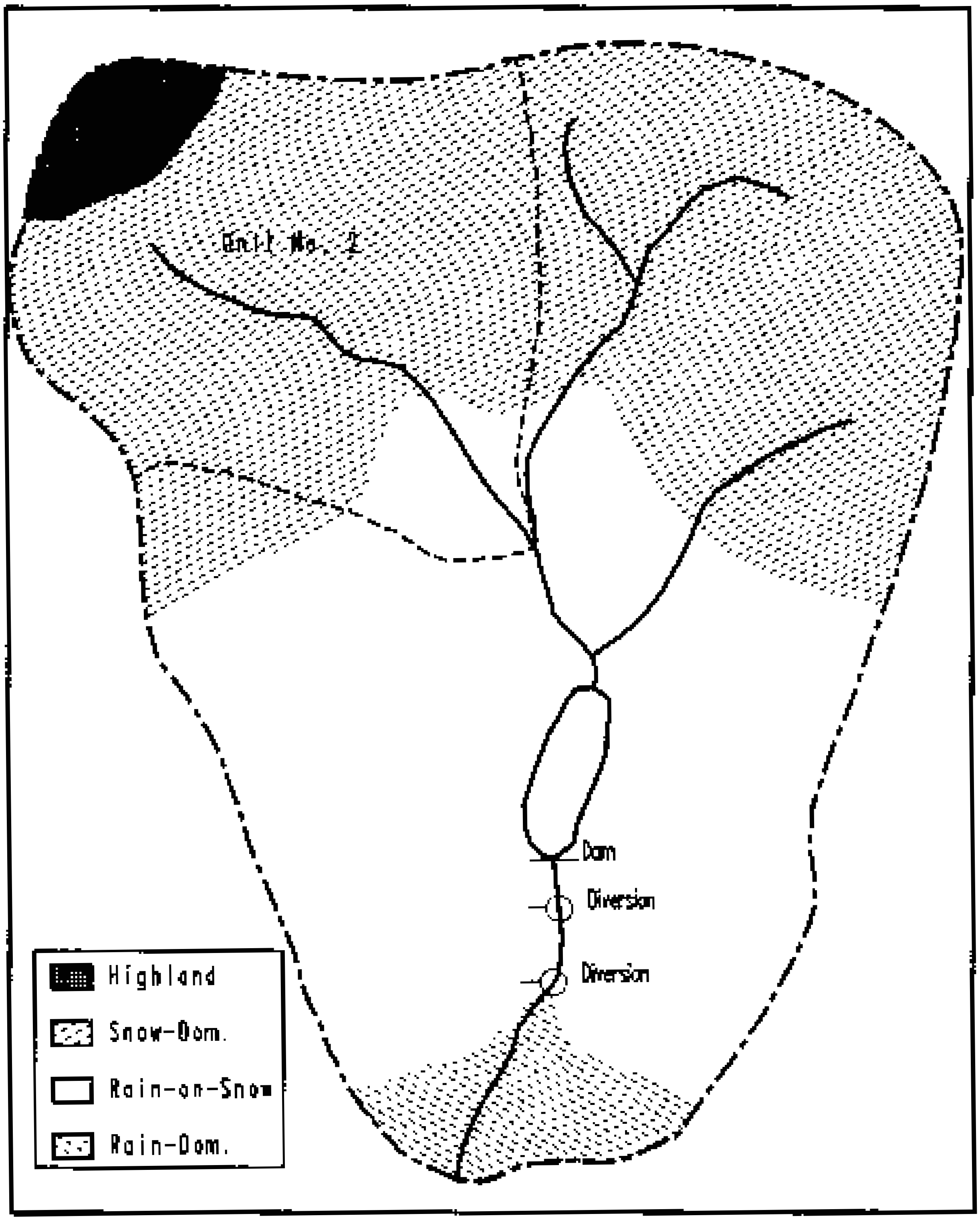


Figure C-3. Example: Form C-1 - Basin Acreage by Precipitation Zone and Land Use/Cover Type.

Hydrologic Analysis Unit: Entire WAU

	Lowland	Rain-dominate	Rain on Snow	Snow Dominate	Highland	Total
Hydrolog. Mature	0	0	2323	4479	85	6887
Intermediate Maturity	0	224	3035	3272	0	6531
Hydrolog. Immature	0	0	1694	1128	0	2822
Total Forested	**0**	**224**	**7052**	**8879**	**85**	**16240**
Non-Forested: Urban	0	0	0	0	0	0
Non-Forested: Agriculture	0	591	880	0	0	1471
Non-Forested: Open Water	0	0	216	0	0	216
Non-Forested: Other	0	0	0	1	382	383
Total Non-Forested	**0**	**591**	**1096**	**1**	**382**	**2070**
Total	**0**	**815**	**8148**	**8880**	**467**	**18310**

SWE_z values calculated above are assumed to represent snow accumulation in hydrologically mature forests; these must be modified to account for variations in accumulation between different land use/cover types. For each polygon (representing a combination of precipitation zone and land-use/cover type), multiply SWE_z by the appropriate ratio given in Table C-4:

$$SWE_{v1} = SWE_{z1} \times R_{zv}$$

$$SWE_{v2} = SWE_{z2} \times R_{zv}$$

Snowmelt

Now that an estimate of snow depth for the design storm event has been established, the snow must be melted. This assessment uses the U.S. Army Corps of Engineers (1956) snowmelt equation, which requires estimates of storm temperature, wind speed, and storm precipitation to melt the accumulated snowpack.

Storm temperature varies primarily with elevation. Determine the "average" storm temperature (T_{z1}, °C) for each precipitation zone based on generalized regional lapse-rate equations:

Western Washington	$T = 10 - (0.006 \times E)$
Eastern Cascades and Blue Mountains	$T = 8.5 - (0.006 \times E)$
Northeast Washington	$T = 8.0 - (0.006 \times E)$

where E_z is the average elevation (m) of the precipitation zone; the boundary between the eastern Cascades and northeast Washington is considered to lie along the Okanogan River.

These equations are based on the average maximum temperatures in fall and winter months; temperatures during ROS storms are generally near these seasonal highs. The analyst may attempt to improve estimates by using local data to generate lapse rates.

To estimate a temperature for warmer conditions representing the "unusual storm", add one standard error; if no other data are available, assume standard error = 2°C

$$T_{z2} = T_{z1} + SEE$$

Local *wind speed* is primarily dependent on the vegetative cover, with mature forest canopies significantly reducing the wind speed at the interface between the snowpack and the air. Using representative frequency curves for wind speed during storms (Figure C-6), select the value that is exceeded 50% of the time for the “average” storm (U_{o1}), and 16% of the time for the “unusual” storm (U_{02}). Local data may be used, if available.

For each polygon in the hydrologic analysis unit, modify the wind speed estimates to reflect the influence of land use/cover types, using the equation (Dunne and Leopold 1978):

$$U_{v1} = U_{o1}[1 - (0.8 \text{ x } F_c)]$$

$$U_{v2} = U_{o2}\,[1 - (0.8 \text{ x } F_c)]$$

where U_{v1} and U_{v2} are the modified estimates and F_c is the canopy closure (fractional form; 100% = 1.0). Use direct measurements or estimates of the canopy density for each polygon if time permits and they are readily available. Alternatively, use the canopy closure values given for each land use cover type in Table C-4.

Calculate snowmelt in each polygon using the equation (U.S. Army Corps of Engineers 1956; Harr, 1981):

$$SM_{24/R} = T_z\,[0.133 + (0.086 \text{ x } U_v) + (0.0126 \text{ x } P_{24/R})] + 0.23$$

The calculation is performed for each scenario (combination of precipitation amount, storm type, and vegetative cover condition). If the calculated $SM_{24/R}$ for a given scenario exceeds the estimated snow accumulation (SWE_z), set $SM_{24/R} = SWE_z$; also, if T_z □ 0.23, $SM_{24/R} = 0$.

Determine water available for runoff for each polygon (in cm) by adding calculated snowmelt to precipitation amount:

$$WAR_p = P_{24/R} + SM_{24/R}$$

(Note: If Tz □ 0 °C for a precipitation zone, it is assumed that no snowmelt occurs and all precipitation occurs as snow; therefore, WAR = 0.)

Convert this result to inches.

Multiply the WAR from each polygon by its area (A_p, in ac or mi^2, measured off the map or in GIS); sum the values for all polygons in the hydrologic analysis unit, and divide the sum by the total unit area (A_u), to calculate a unit-averaged WAR:

$$WAR_u = [\Sigma\,(WAR_p \times A_p)_i\,] \;/\; A_u$$

Results of this analysis are summarized on a form labeled *Form C-2 - Summary of Water Available for Runoff* (see example - Figure C-7).

Peak Flow Estimation

This portion of the assessment converts the WAR estimates calculated above into estimates of peak flows at the outlet of the hydrologic analysis units under consideration. The products are flood-frequency curves for the range of return intervals used for the WAR estimate, under each of the assumed storm types and vegetative cover conditions. Peak flow sensitivity is evaluated by comparing flow estimates for different levels of hydrologic maturity. Results of this comparison are used to develop a peak flow sensitivity rating, in consultation with the analysts of channel condition, fish habitat, and public works. The sensitivity rating is delivered to the routing and synthesis modules, where it is used to evaluate whether any hydrologic changes may have significant impacts on public resources.

Storm runoff can be related to discharge with an appropriate model for the watershed. Ideally, the relationship could be established for each watershed based on measured precipitation and streamflow data. It would be of interest to generate the entire flood hydrograph; however, time limitations and data availability may preclude this (especially for level 1 assessments). The standard methods, therefore relies on regression equations for estimating peak discharge, in the absence of more local information. However, more sophisticated models may be used, especially those that generate an entire hydrograph, and are prescribed for use in forested watersheds.

Estimate baseline flood frequency curves

Use estimates obtained earlier in the assessment using the USGS peak flow equations.

Table C-2. Summary of Peak Flow Regression Coefficients, for Regions Shown in Figure C-4

Recurrence Interval, T	Regression Coefficients				Standard Error of Estimate (percent)
	Regression Constant a	Drainage Area b_1	Annual Precipitation b_2	Forest Cover b_3	
Region I					
2	0.191	0.86	1.51	__	24.9
5	.257	.86	1.53	__	24.6
10	.288	.85	1.54	__	26.9
25	.317	.85	1.56	__	31.5
50	.332	.86	1.58	__	35.7
100	.343	.86	1.60	__	40.3
Region II					
2	0.104	0.86	1.51	__	39.8
5	.140	.86	1.53	__	37.3
10	.158	.85	1.54	__	37.1
25	.176	.85	1.56	__	38.5
50	.186	.86	1.58	__	40.7
100	.194	.86	1.60	__	43.5
Region III					
2	0.054	0.86	1.51	__	41.6
5	.073	.86	1.53	__	42.8
10	.082	.85	1.54	__	45.4
25	.092	.85	1.56	__	50.3
50	.098	.86	1.58	__	55.1
100	.102	.86	1.60	__	60.7
Region IV					
2	0.059	0.86	1.51	__	39.3
5	.081	.86	1.53	__	38.5
10	.092	.85	1.54	__	36.9
25	.105	.85	1.56	__	39.9
50	.112	.86	1.58	__	42.4
100	.119	.86	1.60	__	46.0
Region V					
5	0.982	0.90	1.35	-0.21	65.1
10	2.87	.88	1.16	-.23	73.9
25	7.51	.87	1.03	-.25	91.1
50	13.6	.86	.95	-.27	105
100	23.4	.85	.89	-.29	121

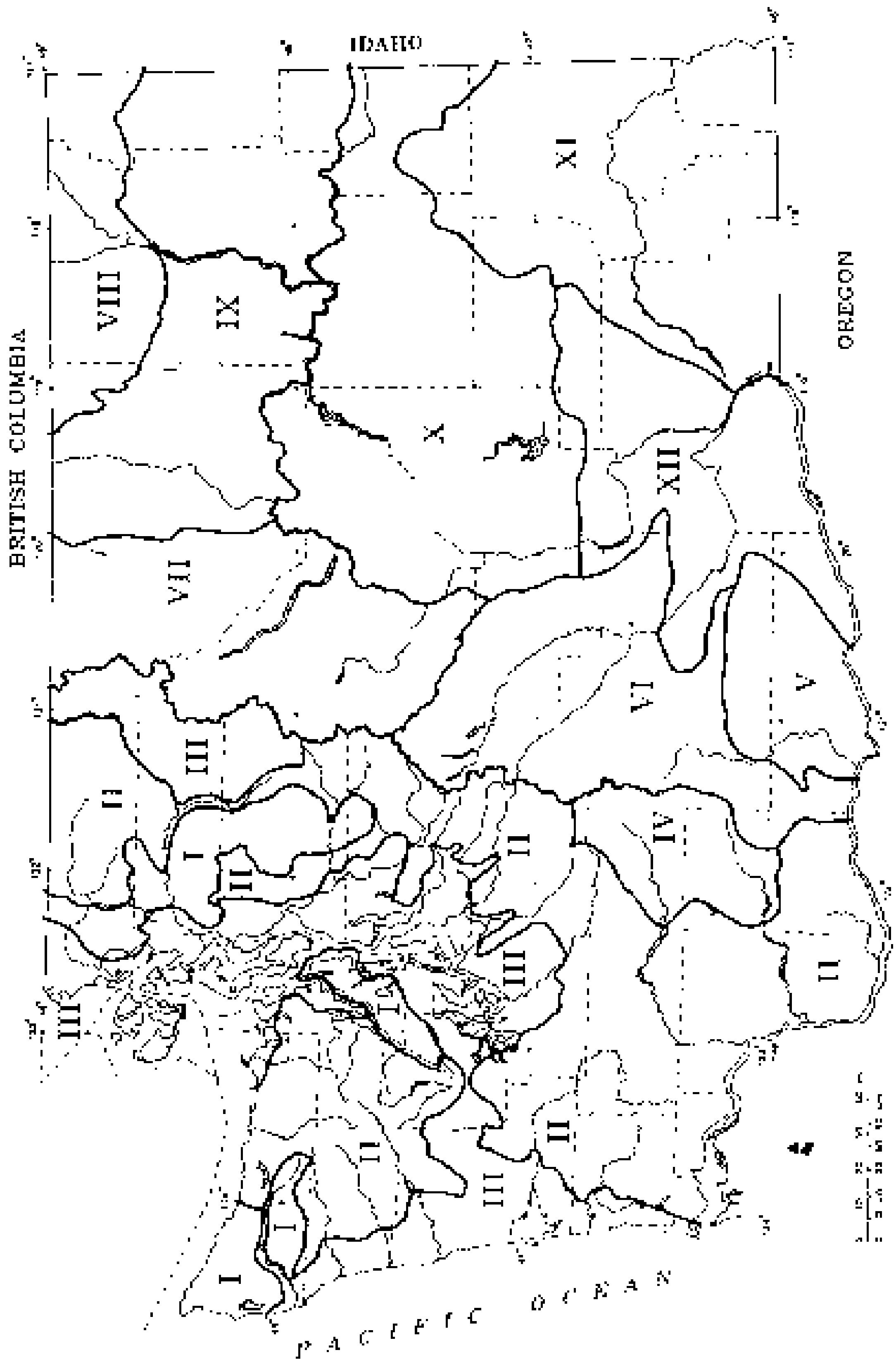
Table C-2. Summary of Peak Flow Regression Coefficients, for Regions Shown in Figure C-4. (Continued)

Recurrence Interval, T	Regression Coefficients				Standard Error of Estimate (percent)
	Regression Constant a	Drainage Area b_1	Annual Precipitation b_2	Forest Cover b_3	
RegionVI					
5	.260	.90	1.35	-0.21	50.2
10	.741	.88	1.16	-.23	45.2
25	1.77	.87	1.03	-.25	48.3
50	2.97	.86	.95	-.27	55.7
100	4.70	.85	.89	-.29	66.2
Region VII					
5	0.263	0.90	1.35	-0.21	75.8
10	.850	.88	1.16	-.23	50.0
25	2.07	.87	1.03	-.25	54.7
50	3.46	.86	.95	-.27	57.1
100	5.45	.85	.89	-.29	59.4
Region VIII					
5	0.508	0.90	1.35	-0.21	41.7
10	1.32	.88	1.16	-.23	44.1
25	2.95	.87	1.03	-.25	47.4
50	4.78	.86	.95	-.27	51.3
100	7.36	.85	.89	-.29	55.9
Region IX					
5	0.186	0.90	1.35	-0.21	62.9
10	.525	.88	1.16	-.23	64.4
25	1.29	.87	1.03	-.25	72.2
50	2.22	.86	.95	-.27	81.0
100	3.60	.85	.89	-.29	91.7
Region X					
5	0.449	0.90	1.35	-0.21	90.1
10	1.16	.88	1.16	-.23	93.1
25	2.54	.87	1.03	-.25	104
50	4.03	.86	.95	-.27	115
100	6.05	.85	.89	-.29	129

Table C-2. Summary of Peak Flow Regression Coefficients, for Regions Shown in Figure C-4. (Continued)

Recurrence Interval, T	Regression Coefficients				Standard Error of Estimate (percent)
	Regression Constant a	Drainage Area b_1	Annual Precipitation b_2	Forest Cover b_3	
Region XI					
5	0.450	0.90	1.35	-0.21	66.6
10	1.36	.88	1.16	-.23	62.2
25	3.59	.87	1.03	-.25	63.3
50	6.61	.86	.95	-.27	72.1
100	11.5	.85	.89	-.29	88.0
Region XII					
5	0.157	0.90	1.35	-0.21	93.6
10	.629	.88	1.16	-.23	54.0
25	1.76	.87	1.03	-.25	56.6
50	3.05	.86	.95	-.27	67.0
100	4.83	.85	.89	-.29	81.8

Figure C-4. Regional Boundaries for USGS Peak Flow Regression Equation (see Table C-2).



Regional Boundaries for USGS Peak Flow Regression Equation

Table C-3. Regression of Snow-Water Equivalent vs. Elevation for Regions Shown in Figure C-5

Region	n	Constant (d_1)	1st-order coeff (d_2) x 10^{-3}	2nd-order coeff (d_3) x 10^{-5}	r^2	Std Error of Est.	Notes
Coastal	22	0.6218	-10.56	2.710	.9280	1.693	
Rain Shadow	20	0.3029	-1.291	2.874	.8347	12.170	
North Cascades	45	-2.098	39.84		.8126	12.656	1
Cedar-Skykomish	34	-1.707	7.741	2.201	.9263	5.935	
Green-Nisqually	49	-5.487	18.08	1.074	.7747	11.647	
Lewis-Cowlitz	53	-2.131	5.533	2.1775	.8186	10.956	4
Lower Yakima-Klickitat	46	-4.683	11.341	1.077	.7067	10.792	2
Naneum-Umtanum	19	-3.492	14.71		.8682	3.170	1, 2
Upper Yakima-Naches	33	-14.615	36.10		.5386	13.086	1, 2
Entiat-Wenatchee	33	-9.859	38.87		.8505	7.762	1
Methow-Chelan	20	-0.1508	4.982	1.316	.8091	9.701	
Okanogan-Sanpoil	29	2.318	-0.4536	0.4589	.7269	2.186	
Columbia-Pend Oreille	32	6.393	-18.575	2.121	.8830	3.979	4
Blue Mountains	19	0	-11.775	1.754	.9093	3.362	3, 4
Columbia Basin	55	0	-2.657	0.8589	.7926	2.001	3, 4

Notes: Regions are as shown in figure C-5; regional boundaries are approximate. Regression factors are calculated from data collated in Brunengo (1995); n = number of stations used in each region; elevations measured in meters, SWE (and the standard error) in centimeters.

1. In some regions, a second-order regression is small improvement, so the first order equation is given. In most cases, however, the first order equations tend to over-estimate the snow depths in the lower (especially the rain-dominated) zones. A segmented (two-line) relationship may be a better fit to the data.

2. In many of the eastern regions, particularly those on the east side of the Cascades, there is typically a wide spread in average snowpacks between high-elevation stations near the crest as opposed to those farther east. Be aware of local conditions in these regions.

3. Some regressions were forced through the origin (0 elevation and 0 snow) to better fit the data.

4. Regressions for some regions included data from adjacent areas of Oregon, Idaho, and/or British Columbia. Information from the rest of the region has not yet been utilized to full potential. In particular, there are >50 snow survey sites in BC below 50°N lat (most not included in these calculations) that could be used in analyses for northern Washington basins.

Figure C-5. Regional Boundaries for Snow-Water Equivalent Regression Equation (see Table C-3).

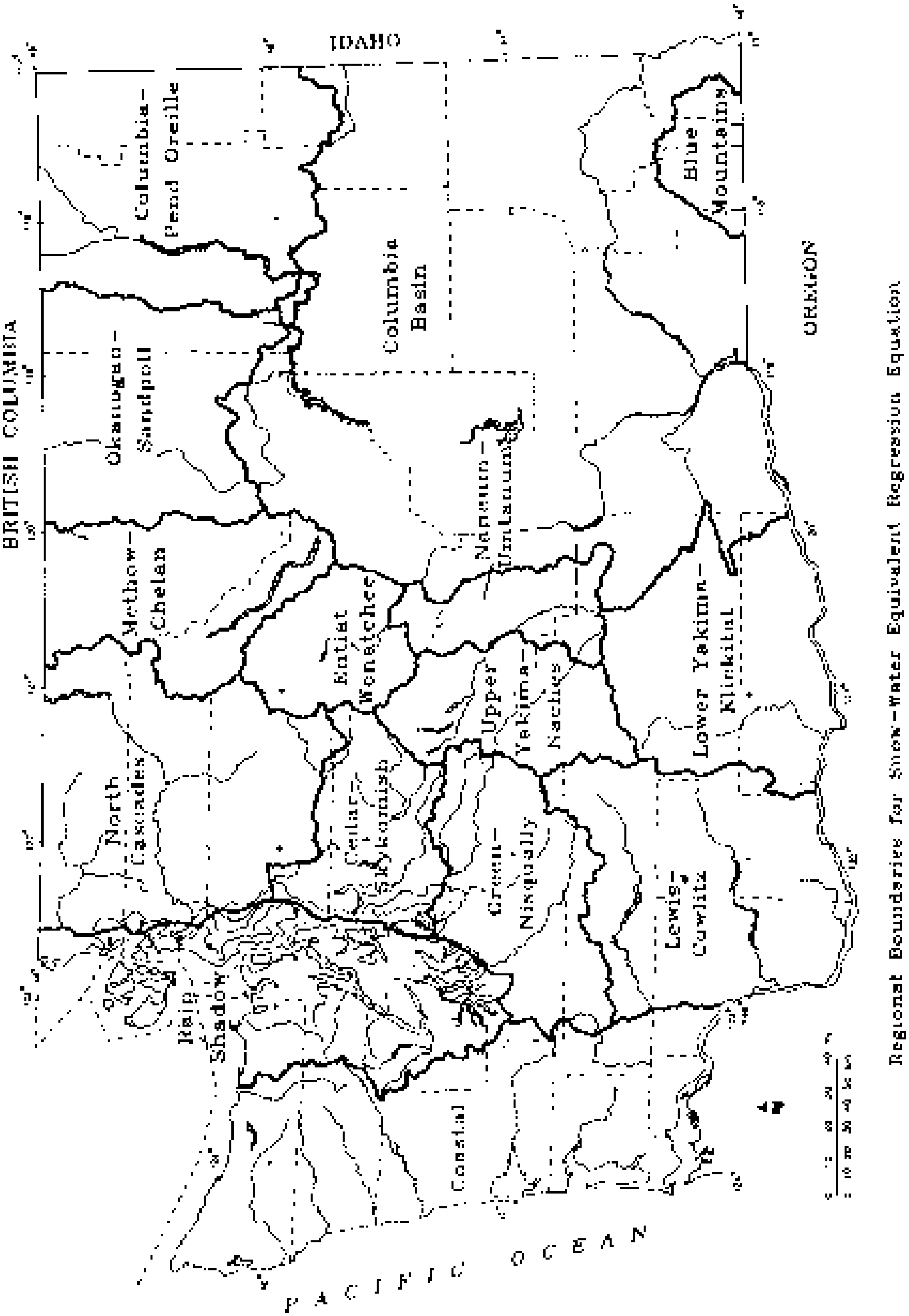


Figure C-6a. Frequency Curves for Wind Speed (Eastside)

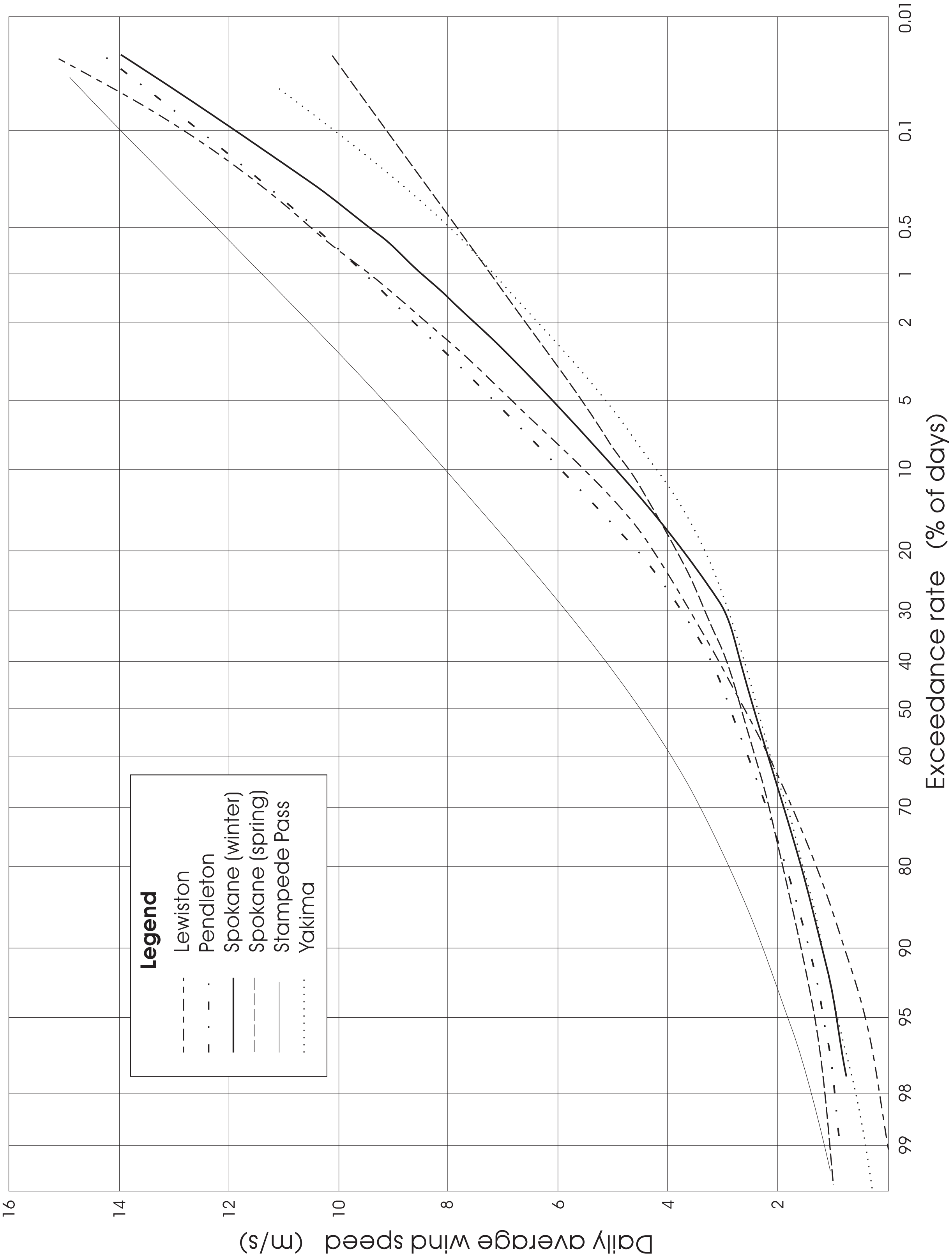


Figure C-6b. Frequency Curves for Wind Speed (Westside)

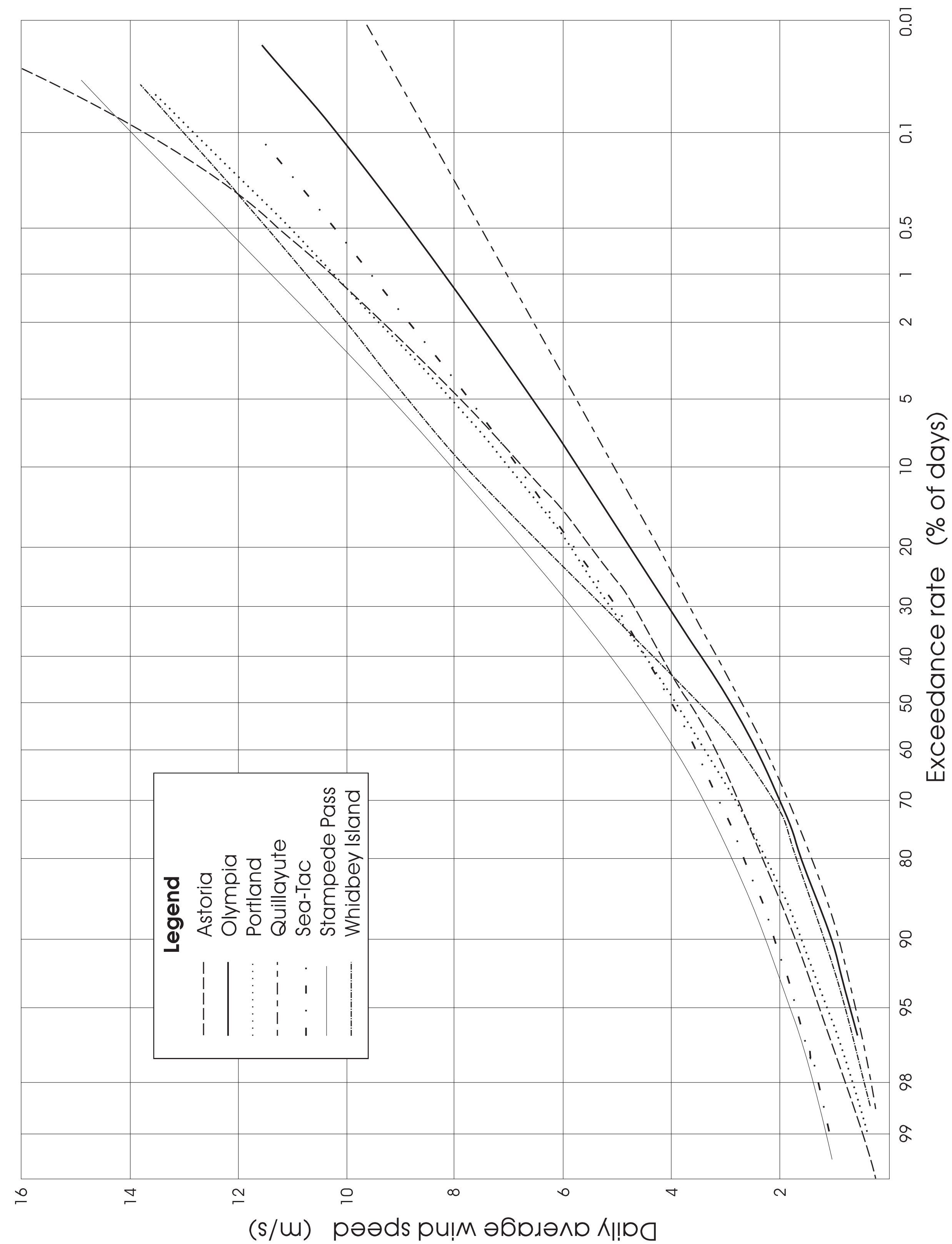


Table C-4. Coefficients for use in snow accumulation and melt calculations.

Land Use/ Cover Type	R (Snow Water Equivalent Ratio)					Canopy Density
	Lowlands	Rain-Dominated	Rain-on-Snow	Snow-Dominated	Highlands	Fc
Forested						
Mature	1	1	1	1	1	0.85
Intermediate	2	1.75	1.5	1.25	1	0.4
Immature	3	2.5	2	1.5	1	0.05
Non-Forested						
Urban	3	2.5	2	1.5	1	0
Agricultural	3	2.5	2	1.5	1	0
Open Water	0	0	0	1.5	1	0
Other	3	2.5	2	1.5	1	0

Vegetation class and description adapted from Pacific Meridian Resources, Inc. 1993.

Snow-water equivalent ratios from Brunengo et al. 1992.

Relate precipitation inputs to flow outputs

The basic hydrologic approach is to predict the discharge associated with various rainfall events. Ideally, both the instantaneous peak flows and hydrographs could be determined. Although several such models exist, they are beyond the scope of the standard assessment. Instead, a simple empirical approach relating rainfall amount and runoff amounts for corresponding recurrence intervals is used.

Although they do not necessarily occur together, we assume that it is appropriate to relate precipitation amounts and discharges having the same recurrence intervals (e.g. the 2-year rainfall and the 2-year flow, each having 50% probability of exceedance; that is, $P_{24/R}$ yields Q_R).

Regress baseline peak flow estimates (dependent variable) against baseline precipitation estimates (independent variable):

$$Q_{R(pred)} = f[P_{24/R}] \qquad (Q_R \text{ in cfs; } P_{24/R} \text{ in inches})$$

Linear regression should provide a function with a reasonably high coefficient of determination ($r^2 > 0.7$).

Estimate Modified Peak Flows

Estimate peak flows for each hydrologic analysis unit by substituting WAR values for each scenario into the regression equation:

$$Q_R(\text{pred}) = f[\text{WAR}]$$

The results from this step are summarized on *Form 3 - Summary of Peak Discharge Estimates* (see example - Figure C-8). The results may also be used to generate modified flood-frequency curves for each combination of storm type and vegetative cover condition.

The output is an estimate of likely changes in peak discharges, under rain-on-snow conditions, for different levels of hydrologic maturity within the hydrologic analysis unit. Write a brief summary of the findings, including any insights obtained from evaluation and comparison of the assessment scenarios.

Interpretation of Results

The relative differences in peak flow discharge at various storm frequencies are the primary interpretative tool for this assessment. The calculations for average and unusual storm events under “maximum hydrologic maturity” conditions assist the analyst to understand the range of possible natural conditions that the watershed may experience. The relative change in discharge at similar storm frequencies with level of hydrologic maturity is the primary means of determining the hydrologic effects of forest management. There may be more water available for the a given rainfall event from a hydrologically less mature watershed, and therefore greater discharge. This would tend to shift the flood-frequency curves to produce more frequent recurrences of a given flood magnitude.

The flood magnitude of greatest concern is usually influenced by the public resources of concern in the watershed. Downstream flooding will focus attention upon the larger storms (Q_{25}, Q_{50}, and Q_{100}), while fish habitat concerns may be more focused on increasing the frequency of the channel-forming discharge (thought to be approximately Q_5 in most steep mountain streams; see Lisle 1981).

For scenarios combining "average" storms and "maximum hydrologic maturity" vegetative cover condition, the resulting peak discharge estimates (depicted graphically as a flood frequency curve) are considered the typical response of an undisturbed, fully stocked forest to storm precipitation amounts at a range of recurrence intervals, and approximately mean ROS-storm temperature and wind, all acting on an average seasonal snowpack. These represent the baseline condition against which increases in peak flows for other scenarios are determined. Scenarios considering "unusual" storms provide an indication of the sensitivity to inputs in warmer and windier storm conditions, acting on a deeper snowpack. Scenarios considering "current conditions" and "minimum hydrologic maturity" represent the responsiveness of the hydrologic analysis unit to the spectrum of land use changes associated with forest practices and other types of disturbances.

Effects of Peak Flow Changes on Public Resources

The significance of the estimated change in peak flows must be related to the likelihood of delivering adverse impacts to public resources. Interpreting the effects of changes in peak flows from land use is confounded by the reality that peak flows are naturally highly variable from year to year. Stream channel dimensions and characteristics are adjusted to accommodate the bankfull (2-year) event in lower gradient self-formed rivers (Wolman and Miller 1960), and the 5-year event in steeper mountain streams (Lisle 1981). However, it is not unusual for stream channels to experience larger but more infrequent events, and they usually do so without significant observable damage.

Figure C7. Example: Form C2 - Summary of Water Available for Runoff

Hydrologic Analysis Unit: Entire WAU

Recurrence Interval	Storm Intensity	WAR [in]		
		Fully Forested	Current Condition	Fully Stocked Young Forest
2 years	Average	12.2	13.4	29.2
2 years	Unusual	12.7	14	29.8
5 years	Average	14.3	15.7	31.8
5 years	Unusual	14.9	16.4	32.5
10 years	Average	16.3	17.9	34.2
10 years	Unusual	17	18.7	35
25 years	Average	18.4	20.2	36.7
25 years	Unusual	19	20.9	37.4
50 years	Average	20.4	22.4	39.1
50 years	Unusual	21.1	23.2	39.9
100 years	Average	22.4	24.6	41.5
100 years	Unusual	23.1	25.4	42.3

Flood control strategies involve managing human development within the 50- or 100-year floodplain, accommodating the natural occurrence of over-bank flooding. Interpreting the effects of changes in peak flows on public resources requires a framework for translating some characteristic(s) of flows directly to the affected resources. For example, flood damage potential depends on the amount of increase in water surface elevation, whereas potential for scour of salmon redds depends on the amount of decrease in streambed elevation.

Fish Habitat

A rationale for conceptualizing the effects of peak flows on fish habitat is based on the mobilization and scour of streambed sediments and the resulting disruption of the egg incubation environment (redds). Stream gravels are mobilized and move as bedload during large peak flow events occurring, on the average, every two to five years (a 20 to 50% probability of exceedance in any year). The depth of the mobile bed layer during the channel-forming discharge is not well documented. Lisle (1989) measured the mobile bed thickness in three California streams with depths ranging from 6 to 15 cm in what appeared to be more stable streams; streams appeared to be unstable when scour depths exceeded 25 to 50 cm.

Salmonids generally bury most of their eggs at depths of between 10 and 45 cm, depending on species (Peterson et al. 1992). Evolutionary strategy would suggest an advantage to burying eggs below the bed layer mobilized by a natural 2-year peak flow event, since scour frequency at shallower depths could affect populations on a nearly annual basis. Larger floods with greater volumes and duration of flow may cause deeper scour of the gravels. Since these storms occur less frequently, they have a lower probability of affecting the entire population, but could have significant effects on the brood in the years in which they do occur.

From a fisheries view, the question is—what flow will mobilize the bed to a depth at which redds are found? Bed load mobilization and transport is reasonably well understood and its occurrence can be related to shear stress associated with depth and velocity of flow (see Leopold et al. 1964). However, our understanding of factors contributing to depth of scour (as opposed to bed mobilization) are not well understood at this time. The shear stress associated with various stormflow discharges relates to the size and volume of sediment mobilized (Richards 1982), although those relationships are not fully established. Hypothetically, a significant increase in shear stress relative to the streambed sediments would result in increased depth and volume of scour. Some geomorphologists have argued that the 5-year flow is the important channel-forming event in mountain streams, implying sufficient scour of the bed and banks.

Unless better evidence is available, we make the assumption that the 5-year event is sufficient to cause deep bed scour in forest stream channels where fish typically spawn. Fish habitat is considered to be significantly affected when either (1) the shear stress increases significantly, or (2) the discharge associated with the 5-year event occurs significantly more often. Although the volume increase necessary to move from a 2-year to a 5-year event varies with channel cross-section, an increase of 20% can be used as a rule-of-thumb to index the difference.

Overbank Flooding and Channel Erosion

Increases in peak flows affect public works primarily by increasing the depth of water on the floodplain or by increasing erosion of channels or levees. Changes in flow depth can be estimated using normal hydraulic routing techniques (see Dunne and Leopold 1978). Overbank flooding is considered significant when the storm flow increases significantly according to accepted planning standards of local, state, or federal agencies.

Channel and levy erosion is more difficult to quantify, although the same rationale for fish habitat changes may also be appropriate for generally predicting channel erosion response to peak flows.

Peak Flow Sensitivity Ratings

Since the effects of changes in peak flows and channel processes associated with forest land use are poorly established, the peak flow sensitivity ratings should be developed directly for each hydrologic analysis unit, utilizing the standards presented above. If the analyst can develop suitable data and rationale for specific locations, the ratings will be better grounded.

The hydrology specialist should consult with the stream channel and fish habitat analysts while performing this analysis. While Level 2 specialists may have the time and capability to perform such assessments, Level 1 analysts are not expected to use this approach. Instead, use relative ratings that provide generalized evaluations of likely channel response based on the geomorphic conceptual model discussed above. These ratings are as follows:

It is assumed that there are no adverse effects for peak flow increases of up to 10%, given the inherent error in the prediction method, and the fact that changes in peak flows of up to 10% are typically below detection limits using standard stream gauging methods. Hydrologic analysis units meeting this criterion are assigned a LOW sensitivity rating.

Figure C8. Example: Form C3 - Summary of Peak Discharge Estimates.

Hydrologic Analysis Unit: Empty WAU

	Discharge and % Increase for Given Recurrence Intervals											
	2-year		5-year		10-year		25-year		50-year		100-year	
	Disch.	% Incr.	Disch.	% Incr.	Disch.	% Incr.	Disch.	% Incr.	Disch.	% Incr.	Disch.	% Incr.
USGS Eqn.	3350		4700		5280		5870		7040		8630	
+ 1 Std. Err.	4000		5050		6550		7900		9375		10700	
Log Pearson Estimate												
+ 1 Std. Err.												
Fully Forested												
1 Avg. Storm	4345		5115		5575		6705		8235		9025	
1 Unus. Storm	4523		5293		5653		6949		8211		9203	
Current Condition												
1 Avg. Storm	4797	10.4	5567	8.8	6127	8.0	7217	8.7	8157	4.6	9420	4.4
1 Unus. Storm	4991	[illegible]	5761	[illegible]	6294	11.4	7413	9.5	8864	8.1	9598	4.4
Fully Stocked/Young Veg												
1 Avg. Storm	5006	[illegible]	5882	[illegible]	6424	14.4	7265	12.9	8292	10.5	9515	5.5
1 Unus. Storm	5293	[illegible]	6033	[illegible]	6700	15.1	7650	[illegible]	9270	13.0	9922	[illegible]

Peak flow increases of more than 10% offer the possibility for adverse effects, and require a level 2 analysis if there is an identifiable potential for downstream flood damages or scour damage to fish spawning areas. Hydrologic analysis units meeting these criteria are assigned an INDETERMINATE sensitivity rating.

Level 2: Analysis of Sensitivity to Peak Flows

Sensitivity analysis is used to estimate the risk of increased flood damage and bed scour caused by increases in peak flows. Both evaluations require estimates of the flood stage for alternative flows. Flood flow values used are those representing fully stocked forest sites and those generated for either current or potential future forest conditions (whichever is higher). The peak flow recurrence interval to be used for calculating the percentage change in flow is the 2-year event for evaluation of bed mobility potential, and the 50-year event for flood damage.

Peak flow sensitivity analyses are site-specific, in that they depend on channel slope and cross-sectional shape, and evaluation of flow resistance, and the particle-size distribution of the bed. The intensive field data requirements make it difficult to conduct analyses at many locations or to extrapolate results to other locations so it is necessary to work closely with the public works, fish habitat, and channel condition analysts to assure that sites selected for analysis are representative of key potential problem areas.

Flood Damage Potential

Flood damage is directly related to increased flood stages. Analysis of channel cross sections is used to estimate change in flood stage for different flow rates. Grant et al. (1992) provide background information and a computer program that simplifies such assessments based on the analysis of a single cross section. Single cross section assessments of this type assume uniform flow conditions. If non-uniform flow conditions exist, methods which utilize multiple cross sections (e.g. HEC-2 or Shearman 1976) are required. Once the analysis is completed for the different flood flows, the cross sections can be used to estimate flood damage by comparing the change in flood stage and area inundated for the sites in question. MODERATE or HIGH sensitivity ratings are assigned on the basis of the change in estimated flood damage.

Bed Mobility Analysis

Bed mobility analysis is used to determine whether the larger particles in the streambed (usually represented by D_{84}) are likely to be transported at a given flow. Bedload transport equations appropriate for the existing field conditions are used to make the assessment. The predicted bed particle size is then compared to the measured particle size to assess whether or not the bed material is likely to be mobilized for the flow level in question. As an example, if the predicted flow is estimated to move D_{84} particles of 10 cm size and the actual D_{84} for the bed is 5 cm, the potential for bed mobility is high. In contrast, the potential for bed mobility is low if the actual D_{84} for the bed is 30 cm. Thus, the ratio of D predicted (D_p) to actual (D_a) provides a measure of bed mobility potential. The mobility potential is high if $D_p/D_a >> 1$ and low if $D_p/D_a << 1$.

Channel cross-section analysis is also necessary for evaluating bed mobility potential; the reference by Grant et al. (1992) is recommended. In addition, bed-load transport equations are needed to estimate bed particle size movement potential. Not all bed-load transport equations are suited to the large streambed particles found in channels draining forested lands in Washington.

Uncertainty associated with the use of bedload transport equations is relatively high and commonly results in a range in sizes in the value of D_p if different transport equations are used. Thus, it is critical to select the equation that is best suited to the field situation. Even if the best equation is used, there is still considerable margin for error. Thus a range of D_p/D_a values is appropriate for assigning sensitivity ratings of MODERATE or HIGH for bed mobility. As an example, ratings might be set up using ratio values of 1.8 or greater for HIGH, 0.8 to 1.8 for MODERATE and <0.8 for LOW.

Bed mobility tends to be directly proportional to scour, and thus provides an index of scour potential. However, it is impossible to predict the amount of scour because it is not possible to account for sediment supply from upstream sources without more detailed procedures for routing sediment (such as HEC-6). Bed mobility also tends to be directly proportional to sediment supply, and may reflect large supplies of sediments supplied either naturally or from accelerated erosion on the watershed. Low bed mobility may indicate that the channel system is inherently stable and not subject to scour; on the other hand, it can also mean that the channel has already been scoured of finer materials by large natural floods or by increased flooding induced by land management activities. Considering the potential for interactions between bed mobility, watershed sediment supply and present channel conditions, it is essential that sensitivity ratings of moderate and high be interpreted in conjunction with the assessments made in the channel module.

Other Hydrologic Issues

The focus of this module is on estimating land-use induced changes to peak flows associated with rain-on-snow storms. While it is assumed that this phenomenon is most likely to have cumulative effects upon public resources, evaluation of other hydrologic issues may be warranted in certain WAUs.

Seasonal and Annual Water Yield

There is a large body of knowledge on the effects of forest management on water yield (e.g. Helvey 1980; Bosch and Hewlett 1982; Harr 1983; Kattelmann et al. 1983; Troendle 1983). These studies show that for several years after logging, water yield increases throughout the year, with the most pronounced effect occurring during the summer and early fall months. However, some observed decreases in summer water yields have been attributed to harvesting in areas where fog-drip is an important precipitation component (Harr 1982), and in response to establishment of phreatophytic hardwoods in the riparian zone (Hicks et al. 1991). In the former case, measured decreases occurred immediately after harvest and approached pretreatment levels after five to six years (Ingwersen 1985); in the latter case, small decreases in summer water yield occurred after five years and have persisted nearly 20 years after treatment.

In general, increases in water yield attributable to forest harvest are perceived to be a net benefit; consequently, no watershed analysis methods have been developed to formally address this issue. In addition, there are insufficient data on the extent and magnitude of fog-drip to develop a method for evaluating this phenomenon. In the event the analyst believes there is justification to perform an evaluation, it is recommended that the case studies mentioned above be carefully applied and the procedures fully explained.

Spring Snowmelt

Where a persistent snowpack contributes large amounts of spring runoff and rain-on-snow events are less common (e.g. higher elevation watersheds east of the Cascade crest), peak flows generated by snowmelt only (little or no rain) may account for most of the 2- to 10-year flows. Strict application of the ROS analysis in these areas events may give erroneous results, because the snowmelt equation used in the analysis was developed for ROS conditions, where advective heat transfer is the dominant form of energy provided. If the analyst suspects that the WAU is in an area where snowmelt-only peak flows are generated, consideration should be made to applying a more appropriate snowmelt model.

Timing of snowmelt runoff is important in many eastern Washington watersheds because this runoff is vital for irrigation supplies and fish outmigration. Changes in the timing of snowmelt runoff due to timber harvest are not well understood. A number of studies in the Rocky Mountains region have indicated that clearcut timber harvesting causes the stream hydrograph to rise more quickly, but has little effect on recession flows (Troendle and Leaf 1981; Troendle 1983; Swanson and Hillman 1977). Peak discharges are generally increased by substantial harvesting within a basin, but depending on the patterning and schedule of harvest, timing of flow may be desynchronized such that increases in peak discharges are not detectable (Troendle and Leaf 1981).

Road Drainage

Forest road networks (including haul roads, skid trails, and landings) and their associated drainage systems can influence hydrologic response by altering the way water is routed through the watershed. Roads and skid trails are the chief contributors to soil compaction; these surfaces are much less permeable, and more likely to generate overland flow. Road ditches collect surface runoff from compacted road surfaces, in some cases augmented by subsurface flow intercepted by the road cut (Megahan 1972). During storm events, this surface runoff is routed more quickly through the watershed; this, in turn, may serve to increase storm peaks if the road network is well connected to the stream channel network.

In watershed studies involving small basins (0.3 to 5 km^2), road drainage has been linked to statistically significant increases in peak flows where roads and skid trails occupied a high percentage (12%-15%) of the drainage area (Harr et al. 1979; Harr et al. 1975). Other studies have indicated no change or even a significant decrease in peak flows attributable to road construction (King and Tennyson 1984; Cheng et al. 1975). It should be noted that these experimental basins are generally smaller then the hydrologic analysis units evaluated in Watershed analysis; in addition, almost all the peak flows measured in these studies were less then the mean annual peak (2.33 year recurrence interval). In studies involving large forested basins (50-600 km^2), no significant increases in peak flow was detected (Duncan 1986; Toth 1990).

Simple generalizations regarding peak flow response relative to the area occupied by the road network may be tenuous, as additional factors (such as the proximity and connectivity of the road network to the stream channel network) may need to be considered. In addition, the response of many small sub-basins comprising the WAU may be attenuated by desynchronization of sub-basin peaks. Identification of a cumulative effect due to road drainage may only be possible if local effects are large and extensive enough. Evidence of local effects may be evaluated by field inspection of road drainage systems upstream from observed gullying or channel enlargement.

Mixed Land Use

As rural areas undergo conversion, namely a permanent change of land use from forestry to residential or other non-forest land-use, natural hydrologic pathways can be permanently altered. Landscaping and agricultural activities remove stumps and compact soils, radically reducing soil porosity, the effective soil water storage, and the macropore network in the soil, all of which diminish soil infiltration rates. Soils disturbed in this way produce surface flows more often and in greater quantities than forested soils because the soils are saturated more frequently as the precipitation rate exceeds the infiltration rate more often. Storm flow peaks from these soils are typically double those of forest soils (Booth 1989). The annual flow volume also significantly increases because of increased storm flow volumes and reduced total evapotranspiration.

Hydrology Assessment Report

The hydrology assessment report organizes and presents results of the hydrologic assessment. The report is a compilation of key work products, maps and narrative summarizing interpretations. Narrative may be on the order of only several pages in length, and should provide a concise discussion of results of each section of the analysis module. While the hydrologic assessment report should be concise, it should be complete enough so that, together with other module products, it provides the input necessary for the synthesis and prescription phases of watershed analysis where the information developed in the analysis modules is incorporated into land use decision making.

Realistically, there will not always be the type of data or information available that the analyst would desire for high confidence in the analyses and interpretations. Assessment of the confidence level possible based on available information is important for decision-making based on these analyses. The degree of confidence that can be assigned to the products of this assessment depends upon a number of factors. Considering the amount, type, and quality of available information, analysts should determine their relative confidence in the interpretations based on each work product. Other factors to consider may include (but are not limited to) extent of field work, experience of the analyst, and multiple lines of evidence for inferred changes.

Hydrology Assessment Report

I. Title page with name of watershed analysis, name of module, level of analysis, signature of qualified analyst(s), and date

II. Table of contents

III. Maps
- Current land use and vegetation cover (map C-1)
- Hydrologic Analysis Unit (HAUs) maps (map C-2)

IV. Summary Data
- Basin acreage by precipitation zone & land use cover for each hydrologic unit (form C-1)
- Summary of water available for runoff for each analysis unit (form C-2)
- Summary of peak discharge estimate for each analysis unit (form C-3)

V. Summary Text
- Narrative describing current watershed land use patterns, structural features, and flood and disturbance history
- Summary of methods, analysis, and results for peak flow analysis
- Summary of methods, analysis, and results for runoff analysis
- Descriptions of any deviations from the standard methods and why the changes were necessary
- Summary and justification for peak flow sensitivity ratings
- Recommendations for Level 2 (at Level 1 only)
- Statement of the author's confidence level in the analysis and results
- Does module report address all critical questions?

VI. Other Information (optional)
- Monitoring strategies and design and implementation suggestions
- Learning resources (a.k.a., references, bibliography) section
- Acknowledgments section

Module Project Management

The module project management checklist is provided to assist the module leader and team members to schedule tasks and review interim and final module products. It is not a requirement of watershed analysis.

Table C-6: Hydrology Project Task Checklist

Review	Task	Schedule	Complete
	Analysis materials in place		
	Startup meeting—brief team on process and intent. Schedule module tasks.		
	Map Hydrologic Units—Complete Hydrologic Unit worksheet (Form C-1).		
	Produce Hydrology Unit map on mylar overlay (Maps C-1 and C-2).		
	Provide hydrologic map to channel analyst.		
	Meet with fish and channel analysts for input on analysis sites and select analysis sites.		
	Perform historic trend analysis; complete the annual peak flow worksheet (form C-2).		
	Review products and checkoff with team:		
	Perform hydrologic modeling: Water-available for runoff and peak flows; complete forms C-2 and C-3.		
	Level 1 teams make sensitivity calls based on estimated change in discharge; complete narrative assessment. Level 2 teams continue with channel cross-section analysis.		
	Level 2 teams calculate changes in flood depths or bed shear stress at selected channel locations to evaluate potential effects of changes in discharge. (Complete narrative assessment).		
	Team meeting: review results and interpretations.		
	Produce module report.		
	Review module report.		

Acknowledgments

This module represents the results of many people over the course of several years. The individuals that contributed to the scientific content of this module include Matt Brunengo, Terry Cundy, Walt Megahan, Kate Sullivan, Kevin Lautz, Todd Bohle, Steven Toth and Curt Veldhuisen. Lynne Miller drafted the first version. Cartographic support was provided by Lori Adkins and Nancy Eberle.

Form C-1 - Basin Acreage by Precipitation Zone and Land Use/Cover Type

Hydrologic Analysis Unit: ______________________

	Lowland	Rain-dominated	Rain on Snow	Snow-dominated	Highland	Total
Hydrolog. Mature						
Intermediate Maturity						
Hydrolog. Immature						
Total Forested						
Non-Forested: Urban						
Non-Forested: Agriculture						
Non-Forested: Open Water						
Non-Forested: Other						
Total Non-Forested						
Total						

Form C2 - Summary of Water Available for Runoff

Hydrologic Analysis Unit ________________________

Recurrence Interval	Storm Intensity	WAR [in]		
		Fully Forested	Current Condition	Fully Stocked Young Forest
2 years	Average			
2 years	Unusual			
5 years	Average			
5 years	Unusual			
10 years	Average			
10 years	Unusual			
25 years	Average			
25 years	Unusual			
50 years	Average			
50 years	Unusual			
100 years	Average			
100 years	Unusual			

Form C3 - Summary of Peak Discharge Estimates.

Hydrologic Analysis Unit:

	Discharge and % Increase for Given Recurrence Intervals											
	2-year		5-year		10-year		25-year		50-year		100-year	
	Disch	% Incr	Disch	% Incr	Disch	% Incr	Disch	% Incr	Disch	% Incr	Disch	% Incr
USGS Eqn												
± 1 Std. Err												
Log Pearson Estimate												
± 1 Std. Err												
Fully Forested												
+ Avg. Storm												
+ Unus. Storm												
Current Condition												
+ Avg. Storm												
+ Unus. Storm												
Fully Stocked/Young For.												
+ Avg. Storm												
+ Unus. Storm												

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